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TITLE: THE MAFIA APPROACH TO SOLVING MAXWELL'S EQUATIONS IN THREE DIMENSIONS

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The MAFIA Approach to Solving Maxwell's Equations in Three Dimensions*

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ABSTRACT

The acronym MAFIA[Klatt, 1986] stands for the solution of Maxwell's equations by the Finite Integration Algorithm and is the name given to a set of codes intended for use in the computer-aided design of three-dimensional magnets, rf structures, and structures in which wake-field effects are important. This paper gives a brief description of the algorithms employed in both the time- and the frequency-domain solvers of the MAFIA collection of codes. Examples of typical accelerator calculations will be presented.

The MAFIA Codes

Figure 1 shows the relationship between the various codes in the MAFIA collection. The individual codes are as follows:

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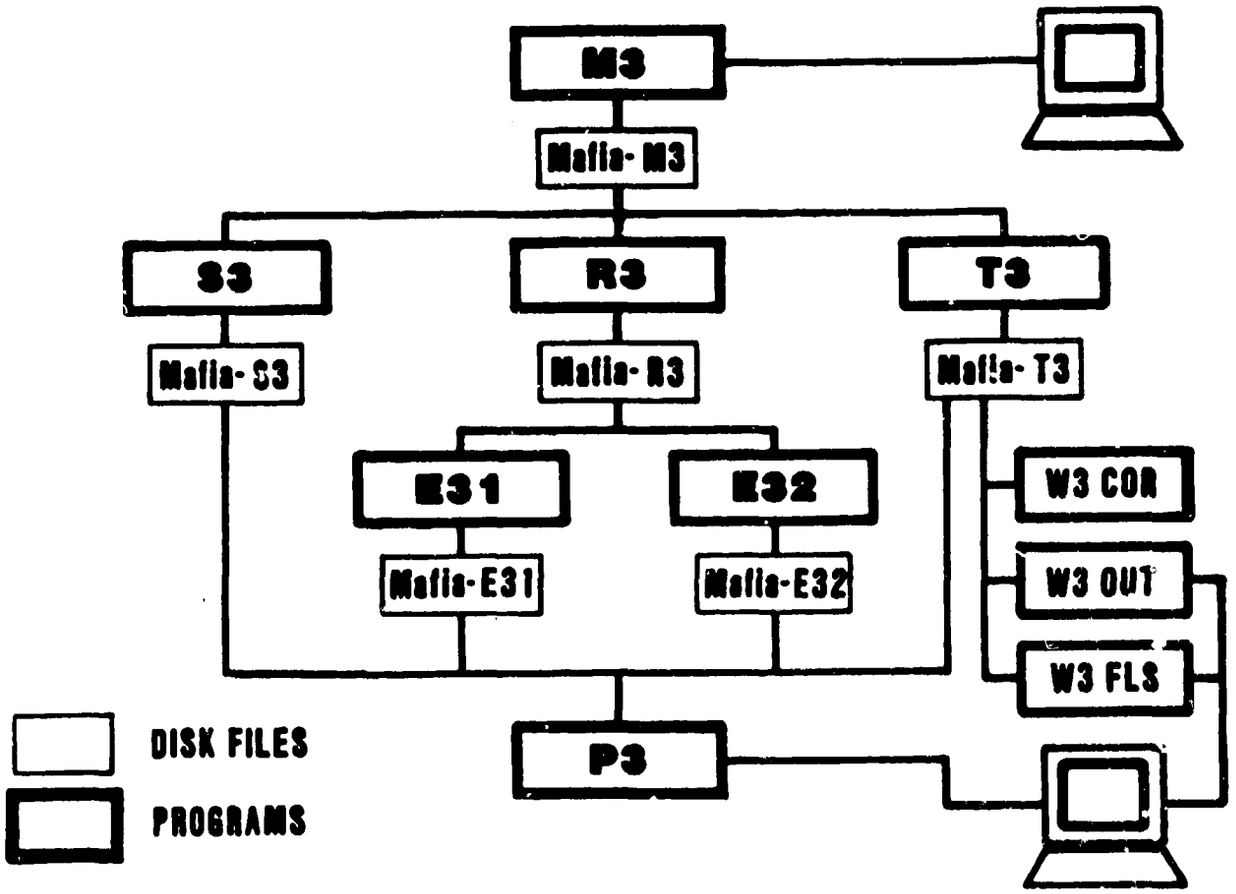

Fig. 1. The MAFIA system with its interrelationships. Depending on the installation, the separate direct access files (e.g., Mafia-M3, Mafia-R3, etc.) may be one single file that is simply extended by consecutive programs.

M3 – the mesh generator used by all the MAFIA codes

S3 – the code that solves electro- and magnetostatic problems

R3 – the code that generates the matrix representation of Maxwell's equations for rf structures; the eigenvalues and eigenvectors of this matrix give the frequencies and electric field components, respectively, of the normal modes of the electromagnetic oscillations of the structure.

E31 and E32 – the codes (only one is used for a given problem) that solve for the eigenvalues and eigenvectors of the matrix generated by R3; E31 is based on a semianalytic procedure[Weiland, 1985] and is a modification of an EISPACK[Smith, 1976] routine; E32 uses a multigrid[Steffen, 1985] method.

P3 – the physics postprocessor that calculates the quantities of physical interest, such as shunt impedance, quality factor, deflection integrals, etc.

T3 – the wake-field code

W3COR, W3OUT, W3FLS – postprocessors for T3.

The collection of programs M3, R3, E31 or E32, and P3 are also known as URMEL-3D.

The FIT Method

The Finite Integration Technique[Weiland, 1984, Weiland, 1985] is an algorithm that produces a first-order approximation to Maxwell's equations by replacing the line and surface integrals, appearing in Faraday's law and Ampere's law, by mean field values times path lengths and areas, respectively. Figure 2 shows the basic cell geometry used in this method.

Note that the electric field components are not defined at a single point, but at the midpoints of the sides of the rectangular cells. The magnetic field components are defined in the center of the faces of the cells and, taken together, form a mesh dual to that defined for the electric field. Only continuous components are involved in the assignment of field values to the mesh,

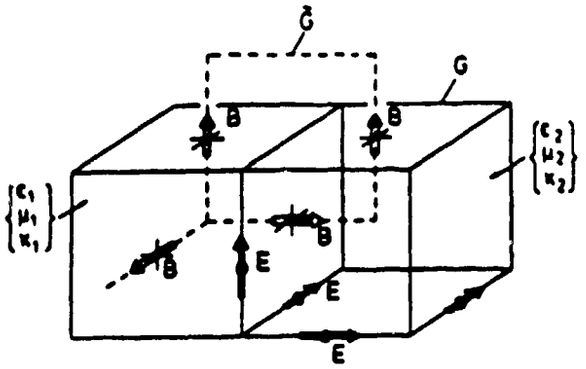

Fig. 2. Ceometry and allocation of field components used in the FIT method.

and thus the cells of the mesh may be individually filled with arbitrary permittive and permeable media. Applying the FIT method to a mesh of N nodes, we can write the discrete form of Faraday's law as

$$\mathbf{C}\mathbf{D}_s\mathbf{e} = \mathbf{D}_A\dot{\mathbf{b}},$$

where **e** and **b** are vectors of length $3N$ that represent the electric field and magnetic induction, respectively; **C** is a $3N$ by $3N$ matrix (containing only the values 0, 1, and -1) that corresponds to taking the curl of a field; $\mathbf{D}_s$ is a $3N$ by $3N$ diagonal matrix containing the lengths of the sides of the mesh cells; and $\mathbf{D}_A$ is a $3N$ by $3N$ diagonal matrix containing the areas of the mesh cell surfaces. Similarly, Ampere's law can be written

$$\tilde{\mathbf{C}}\tilde{\mathbf{D}}_s\mathbf{h} = \tilde{\mathbf{D}}_A(\dot{\mathbf{d}} + \mathbf{j}),$$

where the tilde indicates that the matrix corresponds to the dual mesh. When we take the material distribution into account and use a leapfrog integration technique in the time variable, we find the recursive algorithm for the calculation of time-dependent fields:

$$\mathbf{b}^{n+1} = \mathbf{b}^n - \delta t(\mathbf{D}_A^{-1}\mathbf{C}\mathbf{D}_s)\,\mathbf{e}^{n+1/2},$$

$$\mathbf{e}^{n+3/2} = \mathbf{e}^{n+1/2} + \delta t\,(\mathbf{D}_\epsilon^{-1}\tilde{\mathbf{D}}_A^{-1}\tilde{\mathbf{C}}\tilde{\mathbf{D}}_s\mathbf{D}_\mu^{-1})\,\mathbf{b}^{n+1} - \delta t\,\mathbf{D}_\epsilon^{-1}\mathbf{j}^{n+1},$$

where the superscripts refer to the time step ($t_n = n\delta t$), and $\mathbf{D}_\epsilon$ and $\mathbf{D}_\mu$ are diagonal matrices describing the filling of the mesh with permittive and permeable media. These last two equations are solved by T3; given the initial values of the fields, fields at a subsequent time require only two multiplications of a matrix with a vector, per time step.

If we are interested in free oscillations (i.e., undriven oscillations) of the electromagnetic field, we find that combining Faraday's law and Ampere's law yields a linear eigenvalue problem in which the eigenvalues are the squares of the angular frequency of oscillation:

$$(\mathbf{D}_\epsilon^{-1}\tilde{\mathbf{D}}_\mathbf{A}^{-1}\tilde{\mathbf{C}}\tilde{\mathbf{D}}_\mathbf{s}\mathbf{D}_\mu^{-1}\mathbf{D}_\mathbf{A}^{-1}\mathbf{C}\mathbf{D}_\mathbf{s})\,\mathbf{e} = \omega^2\,\mathbf{e}.$$

For the practical solution of this eigenvalue problem, this equation can be transformed into one in which the matrix is symmetric. The program R3 constructs this symmetric matrix, incorporating material distribution and boundary conditions into the process of construction. A more detailed treatment of the application of this method to problems of electromagnetism may be found in[Weiland, 1986].

Sample Structures

Both the time-domain and frequency-domain solvers have been used to study the effects of cavity asymmetries due to a waveguide feed. (See Fig. 3.)

We have also been using the frequency-domain solver to study asymmetries due to the coupling slots in a side-coupled cavity (Figs. 4 and 5) and to understand the jungle gym slow-wave accelerating structure (Fig. 6). This latter work has been accepted for publication in *Particle Accelerators* [Loo, 1988].

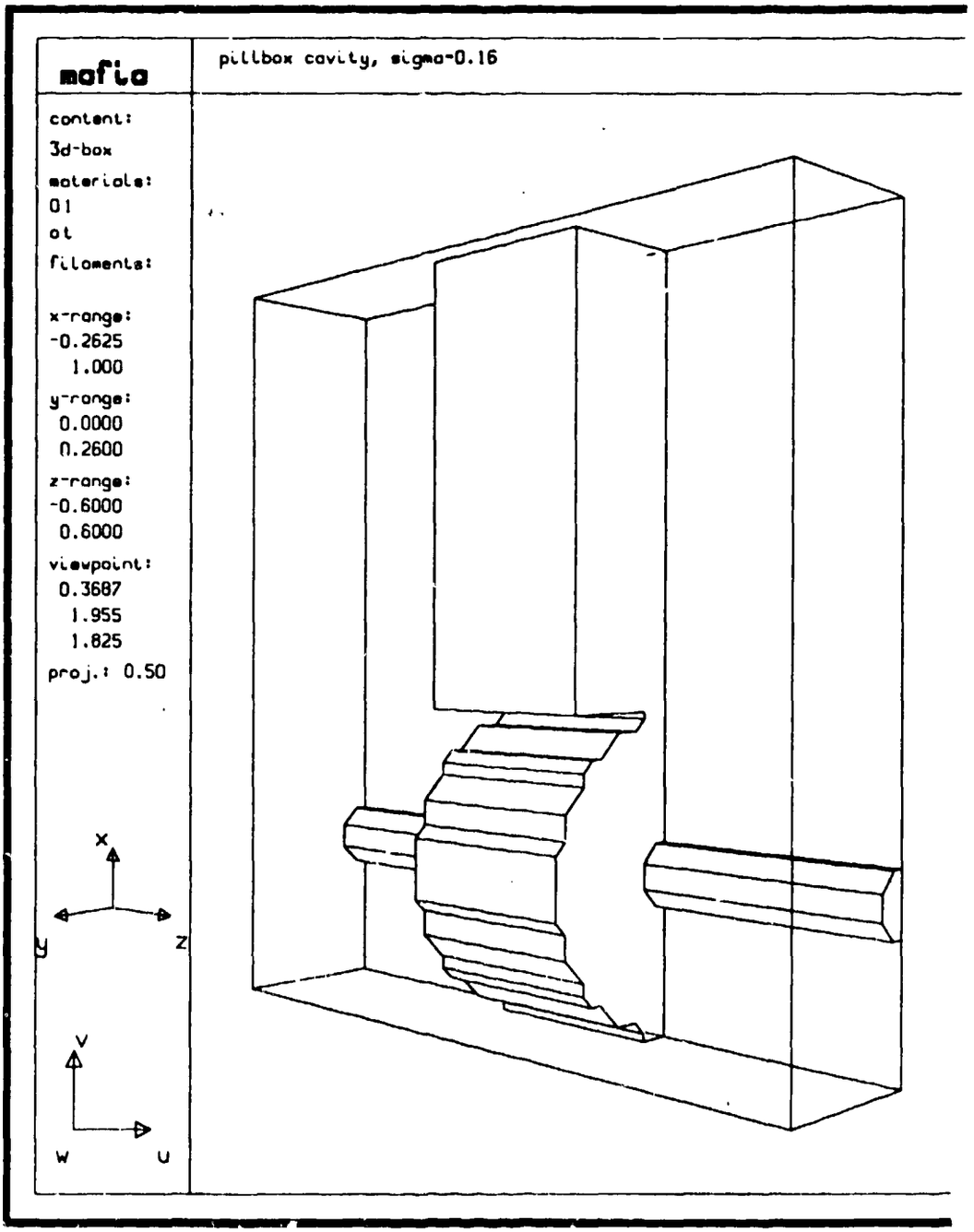

Fig. 3. Cavity used to study the effects of asymmetries due to a waveguide feed.

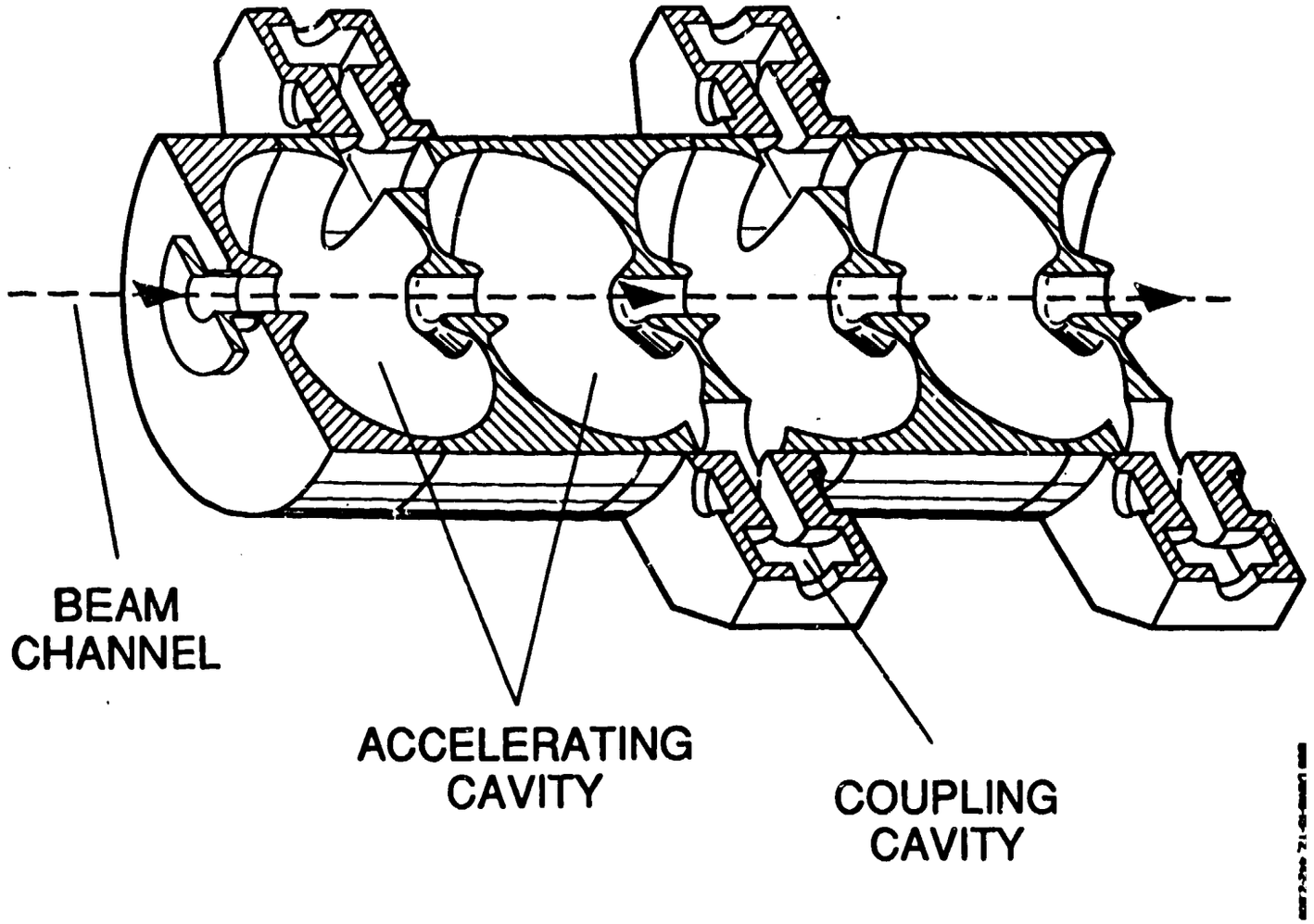

Fig. 4. Drawing of one-half of a side-coupled cavity accelerating structure.

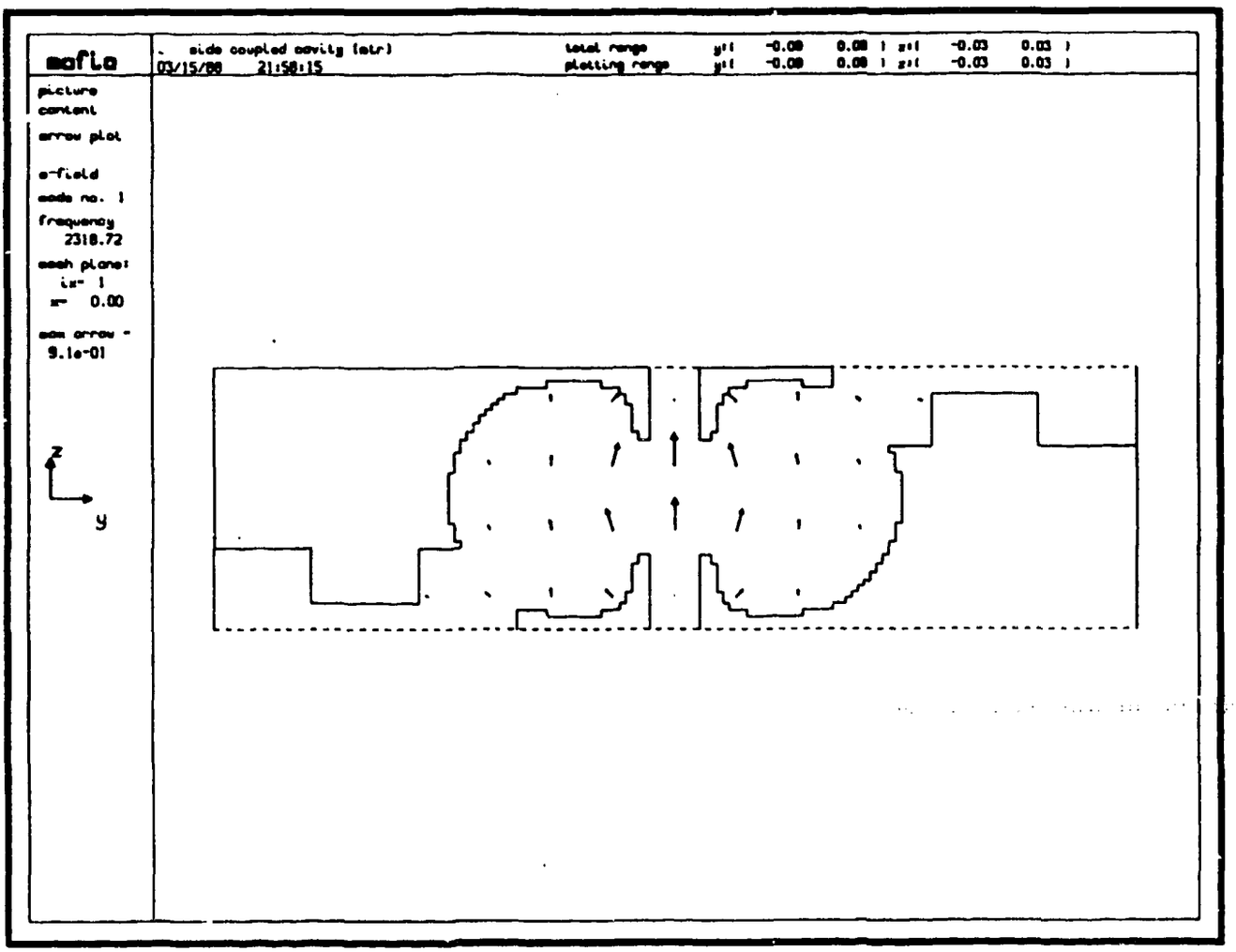

Fig. 5. Computer plot of the electric field in the symmetry plane of a side-coupled cavity.

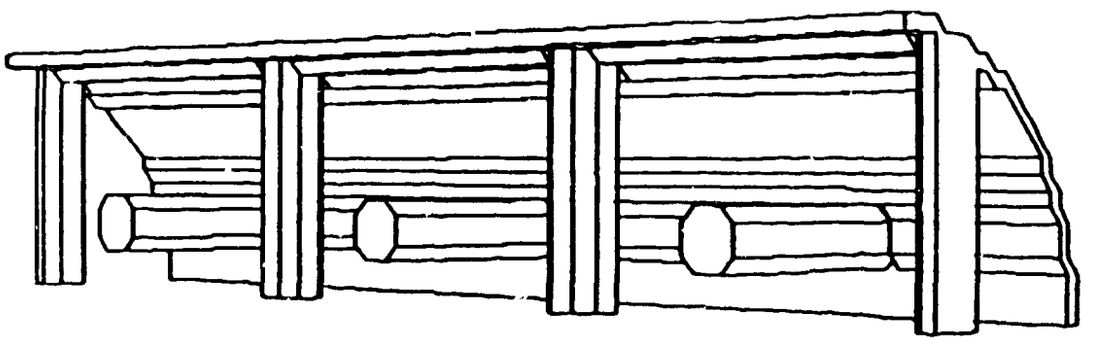

Fig. 6. A computer plot of one-quarter of a three-cell jungle gym acclerating structure.

Availability

The MAFIA codes are written in FORTRAN 77 and currently run on IBM 3081, CRAY, and VAX computers. They are also available to approved users in executable form on the National Magnetic Fusion Energy Center (NMFEC) computers. For more information contact Carol Tull at the NMFEC (phone: 415-422-1556) or Therese Barts at LANL (phone: 505-667-9385).

For those users who want to use the codes at their own installation, there are examples of three graphics interfaces available: DISSPLA on a Los Alamos Cray, PLOT-10 on the DESY IBM 3081, PLOT-10 on the VAX-VMS, and GKS on the DESY IBM 3081. The codes are available without charge to approved nonprofit organizations; for further information contact Thomas Weiland at DESY (Phone: 49-40-8998-3196). Users may not modify nor distribute the codes, and they are asked to be friendly and sometimes patient. Users at other than nonprofit institutions should contact DESY for special contractual arrangements.

Documentation[Cooper, 1987] may be obtained by writing the following address:

Los Alamos Accelerator Code Group
AT-6, Mail Stop H-829
Los Alamos National Laboratory
Los Alamos, NM 87545

The phone number is 505-667-2839.

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